Donald D. Clayton's research career in astrophysics and planetary science is notable for creative innovation in ***five*** major scientific disciplines. His innovations permanently associate his name with each discipline. Firstly, Clayton is a founding pioneer of nucleosynthesis theory (origin of the chemical elements in stars); secondly, Clayton created ideas for a new astronomy based on radioactive gamma-ray-line spectroscopy; thirdly, his predictions based on nucleosynthesis theory motivated a new solid-state astronomy based on the non-solar isotopes contained within STARDUST (dust condensed bearing diagnostic isotopic compositions as a consequence of hot. cooling matter leaving stars); fourthly, his analytic mathematical models of the radioactive-isotope abundances in the Milky Way Galaxy clarified the intimate relationships between the history of star formation in the galaxy and the concentrations of radioactive nuclei in star-forming molecular clouds; fifthly, Clayton conceived how carbon condenses into dust particles within supernovae expansions despite those hot gases having a greater abundance of oxygen than of carbon. The location of each topic within Clayton's autobiography, ***Catch a Falling Star***, is highlighted green. (*e.g.* **Chapter 6**) The following details contain citations to selected seminal papers from Clayton's CV (which is seen at http://claytonstarcatcher.com/files/documents/JournalPub.pdf)

Nucleosynthesis Theory Clayton took outlines of two physical correlations between abundances and nuclear properties from the celebrated review paper [Burbidge, Burbidge, Fowler and Hoyle (1957)] and created the first calculable mathematical models of the *s* process and of the *r* process of heavy-element nucleosynthesis. His 1960s and 1970s papers showed that the details of solar abundances require that they are superpositions of abundance patterns caused by differing neutron irradiation intensities. ["Neutron Capture Chains in Heavy Element Synthesis" *Annals of Physics*, **12**, 331-408 (1961); "Nucleosynthesis of Heavy Elements by Neutron Capture" Ap. J. Suppl. **11**, 121-166 (1965)]. In a subsequent paper of great influence Clayton updated the nuclear data on which the theory is based and the superposition principle of its exposures with colleagues at the Karlsruhe Nuclear Center ["s-process studies in the light of new experimental cross sections: Distribution of neutron fluences and r-process residuals", *Astrophys. J.*, **257**, 821-846, 1982]. Clayton's formulations became the standard model for four decades of subsequent progress on these neutron-capture processes. Important as these processes were for astronomical acceptance of the truth of nucleosynthesis in stars, the *s* process does not create greater net abundance of the heavy elements in our Galaxy because it merely transmutes one heavy isotope into a different heavy isotope. The *r* process, on the other hand, does cause the concentration of heavy-element abundances to increase with galactic time. Clayton then turned his attention to the increase of galactic abundances of the elements between silicon and nickel, and formulated the concept of "nuclear quasiequilibrium" during silicon burning ["Nuclear quasi-equilibrium during silicon burning", *Phys. Rev. Letters*, **20**, 161, (1968); *Astrophys. J. Suppl. No. 148*, **16**, 299, (1968)]. This idea explained how silicon transforms into the elements between silicon and nickel in atomic weight (A=28 to A=62), and why those elements grew to be more abundant with time. Quasiequilibrium also clarified that the abundance peak at iron was created as radioactive nickel in the supernovae themselves. Quasiequilibrium was the first major advance in the theory of nucleosynthesis of new primary galactic abundances since

Hoyle's monumental 1954 paper founding that subject, thereby establishing Clayton as the major new force of nucleosynthesis theory. A prolific period of contributions with his Rice colleagues David Arnett, Stan Woosley and Mike Howard showed that nucleosynthesis leadership had passed from Caltech to Rice. ["Thermonuclear origin of rare neutron-rich isotopes**"**, *Phys. Rev. Letters*, **27**, 1607, (1971) and *Astrophys. J.*, **175**, 201, 1972); "The explosive burning of oxygen and silicon", *Astrophys. J. Supplement Series*, **26**, 231-312, 1973]. Still later, Clayton's group at Clemson showed how abundant ^{48}Ca became so abundant in the Galaxy ["^{48}Ca Production in Matter Expanding from High Temperature and Density", *Astrophys. J.*, **462**, 825-838 (1996)] owing to a relatively rare form of Type Ia supernovae in which the appropriate quasiequilibrium occurs and how the mass A=95 and A=97 isotopes of molybdenum become dominant in supernovae STARDUST ["Molybdenum Isotopes from a Supernova Neutron Burst", *Astrophys, J. Letters,* **540**, L49-L52 (2000)]. Dozens more contributions can be seen in Clayton's journal publications.

Chapters 7, 9 and 18 in *Catch a Falling Star*.

Gamma-Ray-Line Astronomy of Radioactive Nuclei The creation of gamma-ray-line astronomy as an empirical test of explosive nucleosynthesis in stars was recognized in the AAS *Centennial Volume* as one of the 50 most influential astrophysics papers of the 20th century. ["Gamma-ray lines from young supernova remnants", Clayton, Colgate & Fishman, (1969) *ApJ*, **155**, 75-82] This high-energy spectroscopic astronomy has blossomed with numerous results and become a top target for future space astronomy missions, as it already was when *Compton Gamma Ray Observatory* was being prepared for launch two decades ago by shuttle *Atlantis*. CGRO was the second of NASA's Great Observatory missions, and Clayton was a Co-Investigator on its proposal. His work to establish this field is best summarized in his chapter "Cosmic radioactivity: a gamma-ray search for the origins of atomic nuclei", in *ESSAYS IN NUCLEAR ASTROPHYSICS*, Barnes, Clayton & Schramm, eds., pp. 401-426 (Cambridge University Press, 1982). This *CGRO* observatory established line gamma rays as a successful new astronomy ["The ^{57}Co Abundance in Supernova 1987A", *Astrophys. J. (Lett.),* **399**, L141-L144 (1992); "Hard X rays from Supernova 1993J", *Astrophys. J. (Letters)* **431**, L95-L98, (1993); "*CGRO*/OSSE Observations of the Cassiopea A Supernova Remnant**",** *Astrophys. J.*, **444**, 244-250, 1995]. Clayton had initially opened this field in 1965 with an idea based on the *r* process ["Radioactivity in supernova remnants", *Astrophys. J.*, **142**, 189-200, 1965] Since 1996 Clemson University has cosponsored an annual conference "Astronomy with Radioactivity" jointly with the Max-Planck Institute for Extraterrestrial Physics near Munich as a way to debate its new findings. http://www.mpe.mpg.de/gamma/science/lines/workshops/radioactivity.htm.

Chapters 8, 11, 17 and 18.

STARDUST Astronomy A new astronomical discipline based on isotopic analysis of chemical elements in STARDUST found in meteorites was Clayton's third great achievement for astronomy. His 1970s papers [*e.g.* "Extinct radioactivities: Trapped residuals of pre-solar grains", *Astrophys. J.*, **199**, 765-69, 1975; "^{22}Na, Ne-E, Extinct radioactive anomalies and unsupported ^{40}Ar", *Nature*, **257**, 36-37, 1975; "Precondensed matter: Key to the early solar system", *The Moon and Planets*, **19**, 109-137 (1978)] lay

down the seminal ideas and isotopic diagnostics of stars to be revealed in STARDUST and fell like a shock wave into the field of cosmochemistry. Almost two decades of experimental search were required before intact STARDUST was isolated as presolar dust particles within meteorites and measured in the laboratory for the isotopic compositions of its chemical elements. These dramatic experimental discoveries, mostly at Washington University (St. Louis), confirmed this new astronomy. The predictive success caused Clayton to be awarded [http://www.clemson.edu/ces/astro/People/Clayton/LeonardMedal.html] the 1991 Leonard Medal of the Meteoritical Society. His designation as 1991 Medalist was still controversial to a few who disagreed with Clayton's initial suggested manifestations within the isotopes of Xenon as a cosmic chemical memory. **Chapter 14** The experimental confirmation of Clayton's predictions at Washington University (St. Louis) established a new field of laboratory and theoretical astronomy based on abnormal isotopic ratios (different from our solar system) of the elements in the STARDUST grains. This astronomical science has been recently reviewed by Clayton & Nittler in *Annual Reviews of Astronomy and Astrophysics* **42**, 39-78 (2004). Since 1991, when Clemson hosted the first of a new series of workshops, Clemson University has cosponsored an annual workshop on "Isotopic Anomalies in Stardust" jointly with Ernst Zinner and his colleagues at Washington University (St. Louis), where the first STARDUST particles were studied. http://presolar.wustl.edu/Laboratory_for_Space_Sciences/Presolar_Grain_workshop_2012.html. Clayton continued to lead the interpretation of STARDUST. ["Placing the Sun in Galactic Chemical Evolution: Mainstream SiC Particles", *Astrophys. J*., **483**, 220-227 (1997); "Supernova Reverse Shocks and Presolar SiC Grains", *Astrophys. J*. **594**, 312-25 (2003); "Molybdenum Isotopes from a Supernova Neutron Burst", *Astrophysical Journal Letters,* **540**, L49-L52 (2000)]
Chapters 14 and 15

Galactic Abundance Evolution of Radioactive Nuclei A venerable field of classical astronomy concerns how the abundances of the chemical elements increase in concentration within interstellar gas as the Galaxy ages. That data provided the first proof of nucleosynthesis in stars. Astronomers call it galactic chemical evolution, although it is really the abundances that change. Of special concern to Clayton was the age of the galaxy as measured by the remaining amount of radioactive nuclei. In 1964 Clayton introduced a new way of doing this, one based on the abundances of the stable daughters of radioactive nuclei ["Cosmoradiogenic chronologies of nucleosynthesis**",** *Astrophys. J.*, **139**, 637-63, (1964)]. When Clayton's methods were merged with the traditional ones based on abundances of uranium and thorium, however, no clear picture emerged, and it became evident to Clayton that the main problem was the unclear relationship between the history of star formation in the Galaxy, the history of later infalling pristine gas onto the galaxy, and the abundances within interstellar gas of the radioactive nuclei, which have been continuously synthesized within stars. Spurred by these concerns, Clayton discovered a mathematical solution of galaxies that rendered these relationships transparent. His analytic models were a milestone of galactic theory because they illustrate those interconnections so clearly. ["Galactic chemical evolution and nucleocosmochronology: A standard model", in *Challenges and New Developments in*

Nucleosynthesis, W. D. Arnett, W. Hillebrandt, and J. W. Truran, eds., University of Chicago Press (Chicago), 65-88 (1984); "Nuclear cosmochronology within analytic models of the chemical evolution of the solar neighborhood", *Mon. Notices Roy. Astron. Soc.*, **234**, 1-36 (1988); "Isotopic anomalies: Chemical memory of galactic evolution", *Astrophys. J.*, **334**, 191-195, (1988)] Radioactive cosmochronology has diminished in importance recently as more accurate techniques for determining the age of the Milky Way have been discovered; but the beneficial understanding of galaxies and abundances by astronomers has been permanent. In particular the concentration of short-lived radioactive nuclei in the galaxy was shown by Clayton to have traditionally been theoretically underestimated by a factor 1/(k+1), where k is a number near 2 to 4 that measures the steepness of the rate of decline of the infall of pristine gas onto our galaxy. ["On ^{26}Al and Other Short-lived Interstellar Radioactivity", *Astrophys. J. (Letters)* **415**, L25-L29 (1993)]. The numbers of these short-lived nuclei that were still alive at some level in the early solar system has grown with more experimental discoveries, so that simultaneous solution for all of their abundances became the guiding principle ["Short-lived Radioactivities and the Birth of the Sun", *Space Science Revs.*, **92,** 133-152 (2000)] Crucial for this entire subject was Clayton's description of the importance of the mixing in time among the distinct physical phases of the interstellar gas, each of which contains a distinct concentration of them. ["Extinct radioactivities: A three-phase mixing model", *Astrophys. J.*, **268**, 381-384, 1983]

Chapters 16 and 17

Condensation of Carbon Solids from Oxygen-Rich Supernova Gas When it became apparent to Clayton that Supernova Stardust (named SUNOCONs by Clayton) possessed isotopic signatures that required it to have condensed from hot supernova gas containing more oxygen than carbon, he devised the recipe for growing rare but large (µm) graphite and SiC solids from such gases. This had been thought impossible by geochemists; but Clayton saw that supernova radioactivity, a constant thread of his career, made it possible. These ideas were published over a 12-yr period (1999-2012) during the last phase of Clayton's career ["Condensation of Carbon in Radioactive Supernova Gas", *Science* **283**, 1290-1292 (1999); *Astrophysical Journal* **562**, 480-493 (2001); "Supernova Reverse Shocks and Presolar SiC Grains", *Astrophys. J*. **594**, 312-25 (2003); "Growth of Carbon Grains in Supernova Ejecta"**,** *Astrophys. J* **638**, 234-40 (2006)]. The ideas are summarized and clarified in Clayton's recent review paper ["A New Astronomy with Radioactivity: Radiogenic Carbon Chemistry"**,** *New Astronomy Reviews* , **55**, 155-65 (2011)], in which Clayton advanced his *New Rules for Carbon Condensation*. Clayton's last word in 2012 on this topic is submitted but not yet accepted by referees: ["Equilibrium Condensation Chemistry for Type II Supernovae having Radioactive Destruction of CO Molecules"**,** *Geochim. et Cosmochim. Acta,* (*in press* 2012)] The kineitc chemical model for these works was constructed by Clayton, W. Liu and A. Dalgarno. It shows how huge (for interstellar gas) particles (micrometers in radius) can grow during the supernova expansion owing to the action of "Population Control" [*New Astronomy Reviews* **55**, 155-65 (2011), section 5.5, p. 163] in which oxidation has kept the abundance of carbon nucleations small so that those few can accrete all of the carbon. This entire episode, including warnings by chemists that it could not be correct, bodes today to have established yet another new aspect of carbon chemistry, our most versatile and inscrutable element.

Chapter 19